Antiprotonic atoms and antihydrogen

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I. MATTER-ANTIMATTER SYMMETRY

The discrepancy between the deviation from matter-antimatter symmetry on the cosmic scale on one hand and the so far observed perfect symmetry between particle and antiparticle properties on a microscopic scale on the other hand is one of the big mysteries that has not yet been satisfactorily explained by the standard model (SM) of particle physics. The observed baryon asymmetry in the cosmos of \((N_B - N_{\overline{B}})/N_e \sim 10^{-10}\) [1] is in the SM thought to originate from the three Sakharov conditions i) Baryon number violation, ii) \(C\) and \(CP\) symmetry violation, and iii) deviations from thermal equilibrium during the expansion of the universe. The so-far observed violations of \(CP\) symmetry in the \(K\) and \(B\) meson sector are however too small to quantitatively explain the observed baryon asymmetry and thus other sources of matter-antimatter asymmetry may be explored. Within the Standard Model extension by Kostelecky et al. [2] it is possible to generate a large baryon asymmetry through violations of \(CPT\) [3].

\(CPT\) symmetry ensures that particles and antiparticles have perfectly equal properties. It is the result of a proof based on mathematical properties of the quantum field theories used in the SM, but certain of these properties like point-like particles are not any more valid in extension of the SM like string theory. Thus tests of \(CPT\) by precisely comparing particle and antiparticle properties constitute a sensitive test of physics beyond the SM. Antiprotonic atoms and especially antihydrogen offer the most sensitive tests of \(CPT\) in the baryon sector.

II. \(CPT\) TESTS WITH ANTIPROTONIC ATOMS AND ANTIHYDROGEN

Since more than 20 years, low-energy antiprotons have provided the most sensitive tests of \(CPT\) in the baryon sector. The TRAP collaboration at LEAR of CERN has determined the maximal deviation of the charge-to mass ratio of proton and antiproton to \((Q_{\overline{p}}/M_{\overline{p}})/(Q_p/M_p) + 1 = 1.6(9) \times 10^{-10}\) [4, 5] using a Penning trap. The ASACUSA collaboration at CERN’s Antiproton Decelerator has been performing precision laser and microwave spectroscopy of antiprotonic helium, an exotic three-body system containing a helium nucleus, an antiproton and an electron exhibiting highly-excited metastable states [6]. By comparing the experimentally observed transitions frequencies between energy levels of the antiproton with state-of-the art three-body QED calculations the most precise values for the equality of proton and antiproton mass and charge \((Q_{\overline{p}} + Q_{\overline{\pi}})/Q_p = (M_{\overline{p}} - M_{\overline{\pi}})/M_p < 7 \times 10^{-10}\) [7]) and the antiproton magnetic moment \(\langle \mu_p - \mu_{\overline{p}} \rangle/\mu_p < 2.9 \times 10^{-3}\) [8]) have been obtained.

Antihydrogen \((\overline{H} \equiv \overline{p}e^+)\), the simplest atom consisting only of antimatter, promises the highest sensitivity because its \(CPT\) conjugate system, hydrogen, is one of the best studied atoms in physics. Currently three collaborations at CERN aim at forming antihydrogen and perform precision spectroscopy of its structure: ATRAP and ALPHA have the goal to measure the two-photon \(1S-2S\) laser transition in antihydrogen, that has been determined to a relative precision of \(10^{-14}\) in hydrogen, and ASACUSA aims at measuring the 1.4 GHz ground-state hyperfine transition that is known to \(10^{-12}\) relative precision from the hydrogen maser.

The progress – as is typical for precision experiments – is slow: the first formation of antihydrogen was reported in 2002 by ATHENA [9] (the predecessor of ALPHA) and ATRAP [10] using a nested Penning trap technique [11], the next major step happened in 2010 when ALPHA reported the first trapping of neutral antihydrogen atoms in a Joffe-Pritchard trap [12] (and later announced trapping times of 1000 seconds [13]), and ASACUSA announced the first formation of antihydrogen in a different trap named “cusp trap” [14] which is expected to provide a polarized \(\overline{H}\) beam [15] useful for measuring the ground-state hyperfine structure in an atomic beam [16]. Given this major achievements, first spectroscopy results can be expected within the next few years.

To reach the full potential of the measurements, i. e. a similar precision than was obtained in hydrogen, a much longer time will be needed. The currently only facility in the world providing low-energy antiproton, the AD at CERN, will be upgraded by an additional storage ring ELENA to decelerate antiprotons further and thus increase the number of trapped antiprotons. By the end of this decade another facility called FLAIR might get into operation at the FAIR facility under construction at Darmstadt.
III. GRAVITY OF ANTIMATTER

Using neutral antihydrogen, the gravitation between matter and antimatter can be experimentally investigated for the first time. Scenarios exist where a difference in the gravitational interaction of matter and antimatter can arise, which are part of a general search for non-Newtonian gravity [17]. The AEgIS experiment has been approved at CERN-AD and is about to start just now, aiming initially at a %-level measurement of the gravitational acceleration of the antiproton. A second collaboration GBAR has submitted a letter of intent and is preparing a proposal, so that enhanced activities in this field can be expected in the future.